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Assessing environmental flows of coordinated operation of dams and weirs in the Geum River basin under climate change scenarios

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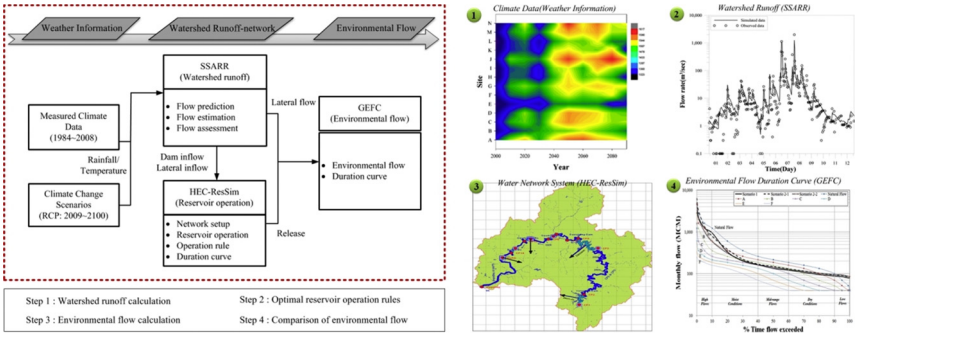
HIGHLIGHTS

- We assessed the environmental management class of the changing riverine environment.
- We assessed countermeasures to mitigate resulting adverse environmental impacts.
- The presence of dam/weir controls optimizes the river flow for socioeconomics and the environment.
- We assessed current and future environmental flows under climate change.

GRAPHICAL ABSTRACT



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ABSTRACT

The International Panel on Climate Change (IPCC) has predicted frequent and severe droughts and floods caused by irregular climatic conditions in the future, making water resources management difficult. Within the field of integrated watershed management, the concept of 'environmental flow' is being increasingly studied. In Korea, the Four Major Rivers Restoration Project was carried out as part of the plan to manage future water resources, particularly in response to climate change. In order to improve comprehensive water resources management, there is an interest in integrating into the operation of the existing dams the multi-functional weirs constructed under the said project. To date, there is an absence of studies comprehensively considering climate change, runoff volume, reservoir operations, and environmental flow, with most of the existing studies focusing only on one or the other of these factors. In this study, we presented a method to evaluate the river environment that considers all the said factors. To evaluate how environmental flow is influenced by the changes in river flow due to climate change and hydraulic structure operation, the Streamflow Synthesis and Reservoir Regulation (SSARR) was used as the hydrological model, HEC-ResSim was used as the hydraulic structures operational model, and the Global Environmental Flow Calculator (GEFC) was used as the method to evaluate environmental flows. RCP climate change scenarios, provided by the Climate Change Information Center (CCIC), a branch of the Korea Meteorological Administration, were applied to analyze the future watershed runoff characteristics of the Geum River Basin under different hydraulic structure operation modes. This study concludes that efficient use of water resources can be achieved through the integrated operation of the dams and multi-functional weirs in times of water shortage. Comparing the results of modelling under a no carbon reduction scenario on one hand, and a scenario in which emissions were reduced on the other hand, differences were found in flows during floods, in the mean annual runoff ratio in accordance with the environment management class, and in the

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environmental flow rating. It appears that a new water resources management plan is required to respond to climate change as indicated by the shift of the flow duration curve to a lower environmental management class (EMC) under climate change scenarios.

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1. Introduction

"Environmental flow" is a rising paradigm in basin management for the conservation of aquatic and aquatic-terrestrial boundary ecosystems. The term is mainly used to indicate the flow regime of a river designed to maintain the river in a specific ecological condition (Smakhtin and Anputhas, 2006). However, the use of the term varies in the literature. For instance, it can also encompass instream flow requirements (IFRs), maintenance IFRs, drought IFRs, and minimum flow (Ministry of Land, Infrastructure, and Transport, 2007; Smakhtin and Anputhas, 2006). The flow regime consists of various components, all of which have unique roles and functions. For example, the deep regions of a river influence the maintenance of the waterway or the flooding of wetlands, while the shallow regions regulate algal growth or fish spawning. Therefore, the best way to ensure a healthy river is to maintain all components of the flow regime as they naturally occur. However, the unprecedented growth in human requirements for water has required the development of various water resources, which has led to changes in the ecology of rivers. Thus, it is nearly impossible to maintain naturally-occurring flow regimes. To improve the self-purification capacity of a river and restore its original functions, a number of actions are necessary, such as creating an environment that can support aquatic life, eliminating pollution sources, and ensuring adequate river flow.

Satisfying water demand for human use while maintaining the health of water resources is a national objective of most, if not all, countries; thus, evaluating and allotting environmental flow are critical (The Nature Conservancy, 2006; Kashaigili Japhet et al., 2007). However, calculation of environmental flow volumes can be complex and difficult due to the lack of appropriate theoretical background or associated data required to quantitatively analyze the influence of change in the flow characteristics on river ecosystems (Hughes, 2001). The evaluation of the hydro-ecological health of a river must be performed using a diverse range of hydraulic, hydrologic, and ecologic data and analytical models. Welsh et al. (2013) introduced the Source Integrated Modelling System (IMS), and describes the individual modelling components and how they are integrated within it and described the methods employed for tracking and assessment of uncertainties, as well as presenting outcomes of two case study applications. Lin and Rutten (2016) studied to extend previous state-of-the-art reviews in the operational management of a network of multi-purpose reservoirs with recent developments and to focus on the application of Model Predictive Control for real time control of a reservoir system.

Korea mandates the setting of instream maintenance flows to maintain the original function and state of the country's streams; however, the calculated final maintenance flows are generally actually average drought IFRs. The Ministry of Land, Infrastructure, and Transport (2000) introduced the concept of river environment, integrating a method of calculating instream maintenance flow, but use of this methodology was not made mandatory. Environmental flows (EF) define the quantity, timing, and quality of river flows needed to preserve freshwater ecosystems while assuring the continuity of human use (Miguel et al., 2018). Insofar as they reduce water availability and condition agricultural and industrial uses, EF represent a constraint, but they also hold out new opportunities for development.

When calculating environmental flows, flow variability is one of the key hydrological characteristics (Bunn and Arthington, 2002) that must be considered. Recently, the International Water Management Institute (IWMI) proposed a method and program, the Global Environmental Flow Calculator (GEFC), that allow for a high-level environmental flow volume calculation within a basin based on the movement characteristics of flow-duration curve (Smakhtin and Eriyagama, 2008). A flow-duration curve represents the relationship between the flow rate and the percentage of time the flow exceeds a given value. It is a hydrological tool that is used to evaluate the flow variability at a specific point of the river. Therefore, the characteristics of the flow-duration curve under specific conditions provide a general idea on the ecological conditions of the target basin. The GEFC analyzes the flow-duration curve at each environmental management class to model the unique runoff characteristics of the river as well as the river flow changes and influences on the aquatic ecosystem due to basin development such as multi-purpose dam construction, and is an effective method given its simple structure. The GEFC was applied to the Geum River Basin in Korea by Kim and Choi (2010), who by analyzing the ratio of mean annual runoff per environmental management class concluded that the results were in line with existing study results (Tennant, 1976; Jones, 2002). Lee and Kim (2011) applied the climate change scenarios from GCMs on the Nakdong River Basin, using the Tank model to calculate runoff and calculated the environmental flow using the GEFC to analyze the influence of climate change. Sood et al. (2017) utilized the GEFC to provide information on global environmental flows for sustainable development. Meanwhile, Salik et al. (2016) provided an assessment of ecological conditions of the Indus Delta under different climate change scenarios by using the ecological health of the Indus River as a proxy variable. They assessed the existing state of the deltaic ecology and categorized it into an arbitrary environmental management class (EMC). However, they did not analyze under different hydraulic structure operation modes and climate change scenarios to integrate climate change and hydrological model, reservoir operation model and environmental flow. Stamou et al. (2018) proposed the novel integrated modelling procedure 3H-EMC for the determination of the environmental flow in rivers and streams; 3H-EMC combines Hydrological, Hydrodynamic and Habitat modelling with the use of the Environmental Management Classes (EMCs) that are defined by the Global Environmental Flow Calculator. However, the study of Stamou et al. (2018) did not consider the operation of dams and multi-functional weirs and climate change.

This study applied the environmental flow calculation method developed by IWMI to the Geum River Basin in Korea, with the objectives of evaluating the present environmental flow and the future environmental flow under different operation modes of the hydraulic structure climate change. The Streamflow Synthesis and Reservoir Regulation (SSARR) hydrological model was used to calculate the natural flow in the 14 sub-basins of the Geum River hydrological system. A network was constructed using Hec-ResSim and then the integrated dam-weir operation model was applied. Using the constructed model, hydrological analysis of one water level station (Gyuam) was conducted considering the integrated dam operations and the integrated dam-weir operations in the hydrological system. Additionally, the GEFC was used to conduct an environmental flow and flow change analysis of the stream and surrounding areas in order to evaluate response strategies to the changing stream environment. Identifying how climate change will affect runoff volume in the Geum River Basin and assessing the variation in downstream water quality due to the operation of the existing hydraulic facilities are critical for the comprehensive water management of the basin system.

2. Materials and methods

2.1. Description of the study area

The study area, the Geum River Basin, is located in Korea at longitude 126°41′–128°25′ and latitude 35°35′–37°05′ (Fig. 1). It is a large basin with an area of 9896.7 km^2. Its main river has a total channel length of 395.9 km. Tributaries include Namdae, Bonghwang, Song, Gap, Miho, Yugu, Ji, and Nonsan; other than Miho, these are all small tributaries with areas of 3–6% of the main river.

The flow duration in the Geum River Basin is strongly influenced (or strongly controlled) by the Daecheong and Yongdam Dams, constructed in 1981 and 2001, respectively. According to the country's Long Term Plan for Water Resources Management (Ministry of Land, Infrastructure, and Transport, 2016), the Geum River Basin has a total annual rainfall of 1240 mm, with a natural runoff volume of 12,800,000,000 m^3 per year. Peak rainfall and runoff occur in July, while the lowest rainfall and lowest runoff occur in January and February, respectively. About 57.6% of the rainfall runs off to the rivers of the basin. The total water use, including for livelihood, industry, and

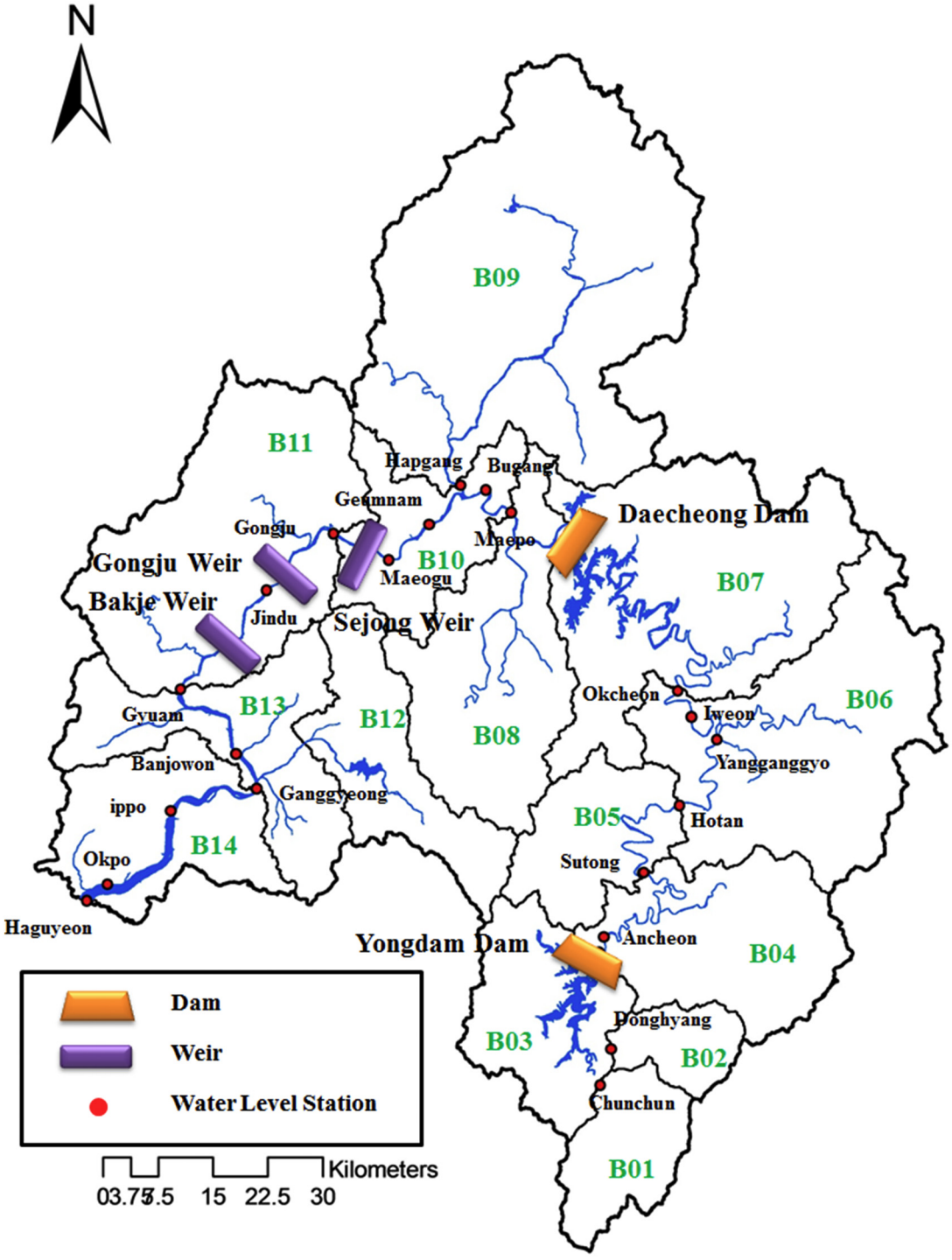

Fig. 1. Study area – Geum River Basin, Korea (Ahn et al., 2018).

Table 1
Multi-regional water supply in the Geum River Basin (Ahn et al., 2014).

Source	Service area	Amount ($10^3 m^3/y$)	Source	Service area	Amount ($10^3 m^3/y$)
Yongdam Dam	Seocheon	12.8	Daecheong	Cheongju	119
	Jeonju	97.3		Cheongwon	64.6
	Gunsan	66.5		Gongju	21.7
	Iksan	38.4		Nonsan	25.6
	Gimje	3.1		Buyeo	9.9
	Wanju	29.2	Geum River	Seocheon	27.4
Daecheong Dam	Asan	81.4	(Buyeo)	Jeonju	7.3
	Cheonan	78.5		Gunsan	27.4
	Danjin	16.8	Estuary dam	Gunsan	45.8
	Yeongi	9.1	Total amount		781.9

agriculture, was 2,648,000,000 m^3 in 2006 (Ministry of Land, Infrastructure, and Transport, 2006). The annual volume of water used from the river and reservoir is 2,522,000,000 m^3, and the volume of subsurface water used is 126,000,000 m^3. The volume of water collected from rivers and reservoirs in Korea represents 36% of the mean annual runoff, which is a much higher rate than the 10–20% in Japan, the United Kingdom, or the United States.

To supply water demand, the Geum River Basin has the large-scale intake source and waterworks shown in Table 1, resulting in 780,000,000 m^3 of water moved per year. As a result of this large-scale water use and movement, the flow duration of the river is constantly altered from its natural state. The control of flow and runoff by hydraulic structures has the primary effect of reducing the flood flow and increasing the drought flow as well as altering the flow duration curve (FDC).

The elevation of the crest and full length of the Yongdam Dam is 268.5 m and 498 m, respectively, while that of the Daechong Dam is 83 m and 495 m, respectively. The planned flood levels of the Yongdam Dam and Daecheong Dam as applied to the model are 265.5 and 80.0 m, respectively. The normal high-water level (experienced in January–July and November–December) is 263.5 m for Yongdam Dam and 228.5 m for Daechong Dam; and the low water level (experienced in August–October) is 76.5 m for Yongdam Dam and 60.0 m for Daechong Dam. The managed level of the Sejong, Gongju, and Baeje Weirs are 11.8, 8.75, and 4.2 m, respectively; their low levels are 10.7, 3.28, and 2.34 m, respectively.

2.2. Overview of the study

The Climate Change Information Center (CCIC), a branch organization of the Korea Meteorological Administration, provides meteorological data based on each Representative Concentration Pathway (RCP) climate change scenario. Of the existing RCP 2.6, 4.5, 6.0, and 8.5 scenarios, this study applied two: RCP 4.5 and RCP 8.5 (please see Section 2.3.2 for a more detailed explanation of the scenarios). The data was applied on a × 1 km grid cells to the SSARR model to calculate the flow going into the hydraulic structures, tributaries, and sub-basins. Each flow volume calculated from the SSARR model was then applied to the HEC-ResSim model (Klipsch and Hurst, 2007). To optimize the water supply in the Geum River water system and surrounding areas, an integrated operations network between the upstream and downstream of the dams was built in the HEC-ResSim model, and the discharge flow at the upstream and downstream ends was then calculated. The tributary intake, calculated using the SSARR model, and the discharge volumes, calculated using the HEC-ResSim model, were then applied to the GEFC model and the changes in the environmental flow under different climate change scenarios were evaluated. As shown in Fig. 2 and Table 2, this study considered the hydrological watershed runoff characteristics in the past (Scenario 1) as well as in the future under two RCP scenarios (Scenarios 2–1, 2–2). The details of the steps followed are as below:

Step 1: Watershed runoff calculation.

- Calculate the runoff amount using the observed rainfall and climate change data from 1984 to 2008 (Scenario 1) and apply it to the SSARR model.
- Analyze the present and future runoff for the period 2009–2100 using RCP4.5 (Scenario 2–1) and RCP8.5 (Scenario 2–2).
- Evaluate changes to the runoff volume by comparing historical and present data (Scenario 1) and present and predicted data (Scenarios 2–1 and 2–2).
- Calculate the intake flow volume to be applied to the reservoir operations model.

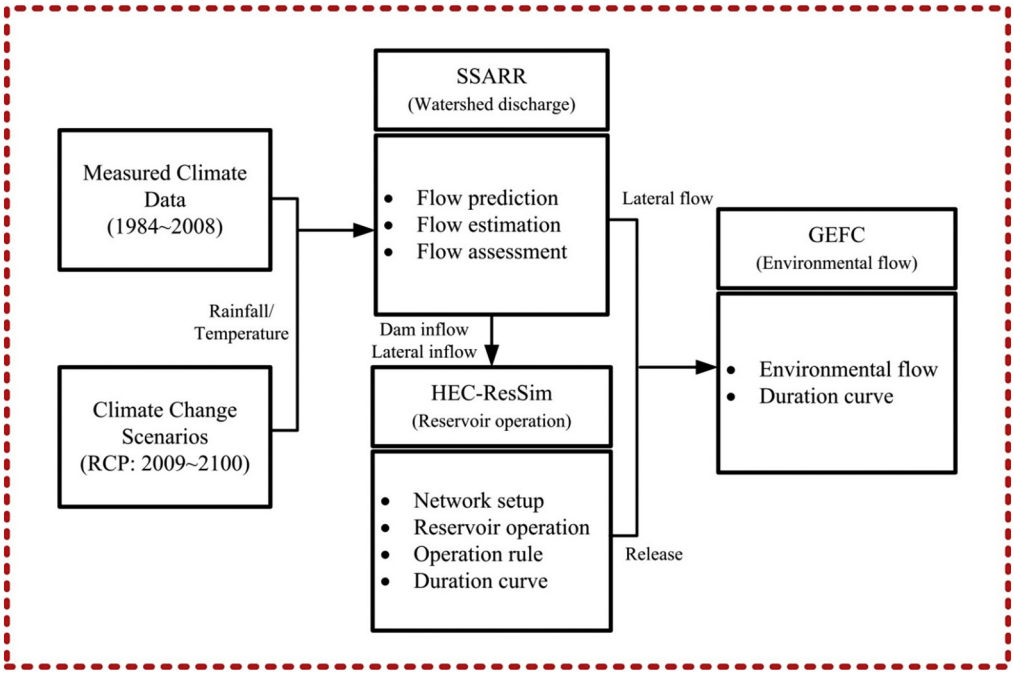

Fig. 2. Flow chart showing the steps followed in this study to assess the effects of climate change on the environmental flow in the Geum River Basin.

Table 2
Different scenarios used in the study.

Weather condition scenario		Hydraulic structure operation scenario	
Scenario 1	Historical data (1984–2008)	Case 1	Natural flow
		Case 2	Operation of individual dams
Scenario 2–1	Future data (2009–2100) Realization of carbon reduction policy through RCP4.5	Case 3	Operation of coupled dams
Scenario 2–2	Future data (2009–2100) Maintain of carbon emission trend through RCP8.5	Case 4	Operation of coupled dams and weirs

Step 2: Optimal reservoir operation rules.

- Apply SSARR runoff volume based on Scenarios 1, 2–1, and 2–2.
- Apply the runoff volumes to the HEC-ResSim model considering the 4 cases below to calculate of discharge volume:

Case 1. Unregulated (no hydraulic structures)

Case 2. Apply planned discharge rate

Case 3. Integrated operations with the dams

Case 4. Integrated operations with the dams and weirs

Step 3: Environmental flow calculation.

- Apply to the GEFC model the dominant flow volume at the Gyuam Water Level Station calculated using HEC-ResSim to analyze the river environmental flow and rating under the above scenarios.

2.3. Scenarios

2.3.1. Water resources development scenarios

As one of Korea's four major river basins, the Geum River System has been subject to multi-year detailed basin studies and field research to obtain highly-reliable hydrological data. The control areas were the Gongju and Gyuam Water Level Stations, located downstream of the Daecheong Dam, where the rating curve equation is rather stable.

Comprehensive analysis of the entire river basin makes the identification of regional flow situations difficult. Therefore, the basin was divided into sub-basins based on the presence and location of multi-purpose dams and key water level stations in the main river and its tributaries. This ensured that the sub-basin characteristics influenced by each hydraulic structure were sufficiently accounted for. ARC-GIS was used to create a 1:25,000 scale map based on the key control points of the Geum River Basin and a 30 × 30 m DEM (Digital Elevation Model) that was used to classify the area into 14 sub-basins, as shown in Fig. 1. For each sub-basin, soil and land use maps of the same scale were utilized to identify basin and flow characteristics, which were important mediating variables of the model.

The Geum River Basin is home to two multi-purpose dams, Yongdam and Daecheong. The Sejong, Gongju, and Bakje Weirs were constructed under the Four Major Rivers Restoration Project in 2012. Before the construction of the Daecheong and Yongdam Dams, the basin could be considered to be in its natural state. However, following the completion of their construction, the physical and hydrological characteristics of the basin changed. The construction of the Sejong, Gongju, and Bakje Weirs led to further changes of the basin.

2.3.2. Climate change scenarios

Climate change will influence the intensity, type, duration, and variability of rainfall, and therefore the availability of water resources. The RCP climate change scenarios provided by CCIC were developed by the Expert Panel on Greenhouse Gas Concentration Scenarios from the Intergovernmental Panel on Climate Change (IPCC). The RCP scenarios are based on radiative forcing value (W/m^2), which is a measure of the influence a given climactic factor such as greenhouse gas has on altering the Earth's radiative equilibrium. The IPCC adopted four RCPs: RCP 2.6, 4.5, 6.0, and 8.5, wherein each number refers to the increase in radiative forcing value in the year 2100 relative to preindustrial levels. The radiative force from sunlight is roughly 238 W/m^2; RCP 2.6, 4.5, 6.0, and 8.5 respectively correspond to 1.1, 1.9, 2.5, and 3.6% increase in the strength of radiative forcing from sunlight. The climate change scenarios for South Korea, provided at a spatial resolution of 1 km, were based on the climate change scenarios for the entire Korean peninsula that were produced by regional climate modelling and statistical downscaling. CCIC provides climate change data for 73 key points of interest and for 230 regions at various administrative levels. It also provides data for RCP 4.5 and RCP 8.5, which are control scenarios covering the next 200 years and which are the RCPs used in this study. RCP 4.5 refers to a scenario where the greenhouse gas reduction policies are generally achieved; In RCP 8.5, the present emission level is not maintained, but rather characterized by increasing emissions over time. The RCP climate change data are based on 2005 as the start year and a model starting from 2006; the data prior to this period are historic climate modelling data.

2.4. Modelling

2.4.1. SSARR

The rainfall-runoff modelling conducted in this study was based on the Streamflow Synthesis and Reservoir Regulation model (SSARR), which is a long-term runoff model developed by the US Army Corps of Engineers. Since its initial development in 1956, SSARR has been upgraded into a GUI Windows-based program. SSARR-2000 is used in applied water resources management.

The multi-layer reservoir method is used in SSARR to track flow. This method allows for parallel movement and delay effects as water passes through the flooded reservoirs. The tracking of each reservoir requires the use of the continuity equation (Eq. (1)) and undercurrent equation (Eq. (2)).

$$I_t = O_t + \frac{dS_t}{dt} \tag{1}$$

$$S_t = T_s O_t \tag{2}$$

In these equations, I_t, O_t, and S_t represent intake, run-off, and undercurrent volumes, respectively, at a given time t. T_s is the undercurrent time.

Using the continuous and undercurrent equations, Eq. (1) can be expressed as Eq. (3); entering Eq. (2) into Eq. (3) leads to a relational equation (Eq. (4)), which can track the runoff at location O_2.

$$\left[\frac{(I_i + I_2)}{2} - (O_i + O_2)\right]\Delta t = S_i - S_j \tag{3}$$

$$O_j = O_i + \Delta t(I_m - O_i)/(T_s + \Delta t/2) \tag{4}$$

Here, i indicates the time when the calculation started, j marks when the calculation ended, and Δt marks the interval of calculations. I_m indicates the mean intake during Δt between the intake and runoff points.

The use the hydrological model was important for predicting the future run-off in the study are under climate change scenarios. Moreover, to predict the environmental flow volume using the GEFC, the natural flow volume had to be must be calculated. Fig. 3 shows the SSARR model of the Geum River system used in this study. The mediator variables were chosen taking into consideration the results of multiple previous studies (Ahn et al., 2014; Ahn et al., 2016; Ahn et al., 2017; Ahn et al., 2018).

2.4.2. HEC-ResSim

2.4.2.1. Model construction and operation rates. The network constructed in this study links the effective storage of Yongdam and Daecheong Dams and Sejong, Gongju, and Bakje Weirs as one reservoir volume, which is an operating rate with a form of equivalent reservoir; it is operated based on the effective storage of each hydraulic structure. Fig. 4 illustrates the coupled operation between two dams, and between a dam and a weir. The overall operation is a water budget analysis, in which a reservoir is considered as a single system where any changes in state are considered.

The operating rules of each structure are as follows. The Yongdam Dam first discharges flow to the Jeonju area, then discharges downstream maintenance flows as the second priority. The third priority discharge is based on the tandem rule: when downstream dams or weirs require flow, the dam discharges downstream if the managed level exceeds the low water level. The Daecheong Dam discharges flow towards the Daejeon area as the first priority, and then operates according to the tandem rule. The dams are operated under changing water levels from their normal high-water levels to low water levels; however, multi-functional weirs must be operated to meet their managed water levels, with the GC (guide curve) rule being the highest-priority rule. The weirs thus only discharge downstream, following the tandem rule, if the flow duration is not maintained at the control point downstream. Diversion (A) and Diversion (B) in Fig. 4 are supplied with the volumes specified in the Basic Plan in the Dam Operations Practical Guide (Korea Water Resources Corporation, 2017), and operate to satisfy the maintenance flow marked at the Gyuam water level station. The dams and reservoirs were operated at a low water level, while the multi-functional weirs were operated at river drought levels prior to weir construction. After weir construction, the maintenance flow volume at the Gyuam water level station was increased by an amount equal to the flow volume increase under the integrated operations of the structures. The 275 days of maintenance flows of streams prior to weir construction are at stream drought levels. It was assumed that the additional flow volume manageable by the multi-functional weirs was equal to the value of managed levels minus stream drought levels; as such, the managed levels were set at stream drought levels.

While each structure is basically operated based on its guide curve, depending on the valid reservoir volumes of the dam or the weir connected downstream, factors such as the minimum desired flow (MDF), minimum release function (MRF), as well as the tandem, surcharge routing, and zone boundary rules are applied based on the

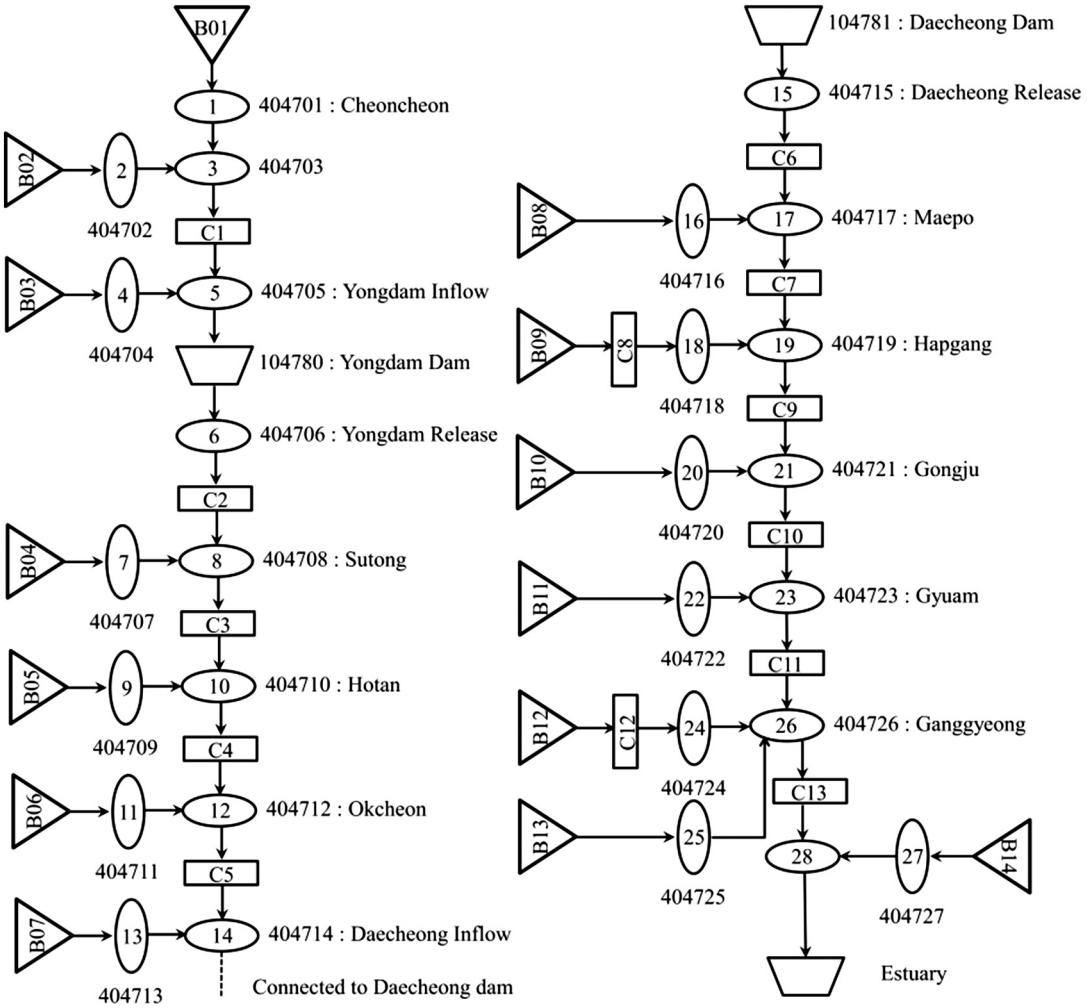

Fig. 3. Streamflow Synthesis and Reservoir Regulation (SSARR) model adapted for the Geum River system (Ahn et al., 2017; Ahn et al., 2018).

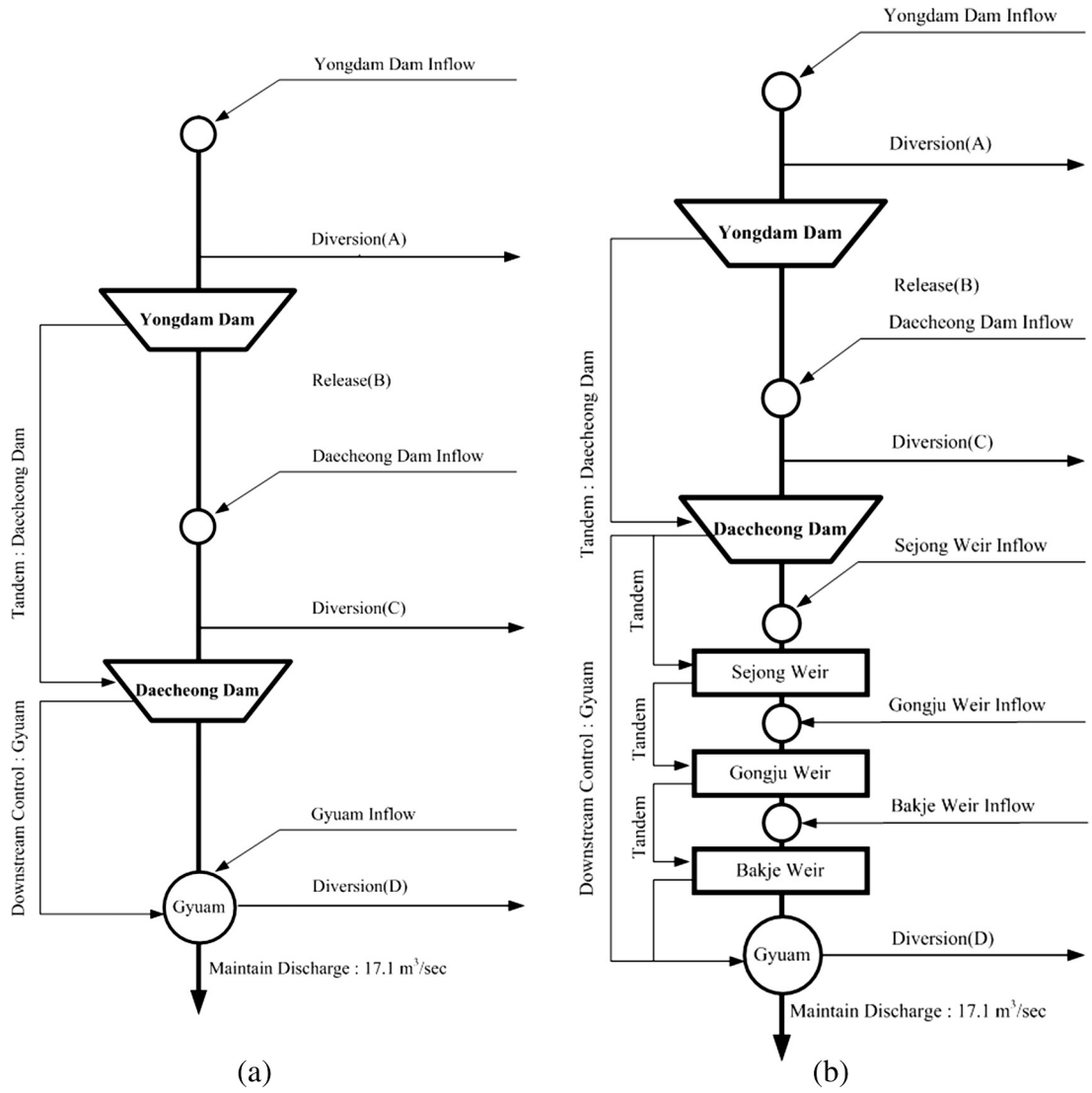

Fig. 4. Operating scenarios of reservoirs and weirs: (a) Flowchart of operation of coupled reservoirs; (b) Flowchart of operation of coupled reservoirs and weirs (Ahn et al., 2014).

reservoir volumes of the dams and weirs constructed into the network, flows at the downstream control points, and the intake volume at each point.

2.4.2.2. Model modification and verification. To evaluate the reliability of the HEC-ResSim model used in this study, the modelled water supply ability was compared with the results of the Water Supply Ability Research on the Geum River System obtained using the HEC-5 model (K-water, 1998).

The target dams were the Yongdam and Daecheong Dams, with a simple connection maintained between the dams to calculate the available amount of water that satisfies the 95% safe yield. The analysis was based on annual reliability, and the discharge volume was controlled while ensuring that the water supply ability was intact over the entire period.

The HEC-5 model allows data input and evaluation at a particular moment of time, while the HEC-ResSim model allows such at month- or day-level. Furthermore, the HEC-5 model utilizes the RL card, which is a command word indicating the water storage capacity according to the water level (e.g. storage level) of the dam and reservoir, to input the water level-reservoir volume. On the other hand, the HEC-ResSim model requires inputs of both the water level and reservoir volume to first analyze the water level then calculate the reservoir volume based on the calculations. Formulated as such, this part implies that the operational conditions of the HEC-5 and HEC-ResSim models were modelled after setting them as equal in order to ensure that the HEC-ResSim model was adequate. The HEC-ResSim model generated reasonable results, as shown in Table 3. Moreover, the calculated volume of water supplied was rather large compared to the existing water supply ability reported in the Long-Term Water Resources Plan. This is because the net water usage has been deducted from the flow data in the Long-Term Water Resources Plan. The reason for the decline in electricity generation is the increased demand in water supply for human use in the areas of Daejeon, Cheongju, Cheonan, and Asan, compared to the

Table 3
Comparison of water supply calculation results (unit: MCM, GWh).

Group		HEC-5	HEC-ResSim		Variation Δ
		Korea Water Resources Corporation (1998)		Ministry of Land, Infrastructure, and Transport (2006)	
Water supply capacity	Yongdam	–	558.2	501.4	Δ56.8
	Daecheong	1603.2	1612.6	1625.0	12.4
	Sum	1603.2	2170.8	2126.4	Δ44.4
Generation	Yongdam	–	16.1	18.4	2.3
	Daecheong	225.2	221.9	111.0	Δ108.9
	Sum	225.2	238.0	129.4	Δ108.6

Table 4
Calculation method for inflow in the HEC-ResSim model (Ahn et al., 2017); "404,705" is a code for inflow location at Yongdam dam, as shown in Fig. 3. (Please see Fig. 3 for similar number strings).

Site	Input value calculation method
Yongdam Dam	404,705
Daecheong Dam	404,714
Sejong Weir	$404721 \times \frac{\text{Upper Area of Sejong Qeir}}{\text{Upper Area of Sejong Weir}+\text{Upper Area of Gongju Gauging Station}}$
Gongju Weir	$(404723-404721) \times \frac{\text{Upper Area of Gongju Weir}}{\text{Upper Area of Gongju Weir}+\text{Upper Area of Baekje Weir}}$
Baekje Weir	$(404723-404721) \times \frac{\text{Upper Area of Bakje Weir}}{\text{Upper Area of Gongju Weir}+\text{Upper Area of Baekje Weir}}$
Gongju Gauging Station	$404721 \times \frac{\text{Upper Area of Gongju Gauging Station}}{\text{Upper Area of Sejong Weir}+\text{Upper Area of Gongju Gauging Station}}$

previous water supply ability report. Based on the flow volume calculated using the SSARR model for each sub-basin, the inflow to the Yongdam and Daecheong Dams for use as input to the HEC-ResSim model was calculated. For the calculation of inflow to the Gongju Water Level Station, the medium-region area division and formulas calculations shown in Table 4 were used for Sejong, Gongju and Bakje Weirs to calculate the HEC-ResSim model inputs. The calculated flow volumes were assigned to flow networks after reviewing the input data using the HEC-DSS (HEC, 1994), a data storage system that allows for saving and modifying time-series data.

2.4.3. GEFC

As mentioned in Section 1, IMWI proposed the GEFC for roughly calculating the environmental flow volume for a target basin through the movement characteristics of a flow-duration curve (Smakhtin and Eriyagama, 2008), since the based on a very simple method proposed by Smakhtin and Anputhas (2006). The GEFC provides an overview of the ecosystem conditions and management outlook based on six environmental management classes (EMC): A, B, C, D, E, and F.

EMCs give a basic idea on the changes to the aquatic ecosystem that can occur depending on the level of environmental protection and management and the ensuing flow characteristics of the rivers. Higher EMCs requires a higher volume of water to be set aside for environmental flow volume and a larger flow variability to be preserved (Kim and Choi, 2010). Classes nearer to A are closer to a natural river environment, while those towards F indicate severe environmental destruction from development (Table 5). Rivers with ecological changes resulting from densely populated areas or basin development tend to have classes ranging from C to F; EMC E and F show critical states where no further development is possible. The GEFC involves the development of a flow-duration curve (FDC) derived from natural flow ("Natural FDC" in Fig. 5), and based on 17 specific probability values (0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9, 99.99%), it moves the curve to the left in stages, as shown in Fig. 5. Table 6 shows the results of estimating the environmental flow using the calculation method described in 2.4.3 GEFC. The % column in the table is based on 17 specific probability values (0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9, 99.99%). The REF column is the flow duration curve (FDC) calculated based on the natural runoff of the watershed. For example, assuming that the natural state has a value of 261 in the case of 40%, it is assumed that the value is changed to 217 by the environmental development of step A. The value of 261 is shifted from 40% to 30% when the step A is developed, 20% in step B, 10% in step C. The moved flow-duration curve sequentially shows EMC from A to F; it assumes that the influence of the reduction in flow volume due to basin development is the variability in the unique flow of the river. Despite its simplicity, it is highly effective.

Table 5
Environmental management classes (EMC; Smakhtin and Eriyagama, 2008).

EMC	Most likely ecological condition	Management perspective
A	Natural rivers with minor modification of in-stream and riparian habitats	Protected rivers and basins. Reserves and national parks. No new water projects (dam, diversions) allowed.
B	Slightly modified and/or ecologically important rivers with largely intact bio-diversity and habitats despite water resources development and/or basin modifications	Water supply schemes or irrigation development present and/or allowed.
C	The habitats and dynamics of the biota have been disturbed, but basic ecosystem functions are still intact. Some sensitive species are lost and/or reduced in extent. Alien species present.	Multiple disturbances associated with the need for socio-economic development, including dams, diversions, habitats modification and reduced water quality.
D	Large changes in natural habitats, biota and basic ecosystem functions have occurred. A clearly lower than expected species richness. Much lowered presence of intolerant species. Alien species prevail.	Significant and clearly visible disturbances associated with basin and water resources development, including dams, diversions, transfers, habitats modification and water quality degradation.
E	Habitats diversity and availability have declined. A strikingly lower than expected species can no longer breed. Alien species have invaded the ecosystem.	High human population density and extensive water resources exploitation. Generally this status should not be acceptable as a management goal. Management interventions are necessary to restore flow pattern and to 'move' a river to a higher management category.
F	Modifications have reached a critical level and ecosystem has been completely modified with almost total loss of natural habitats and biota. In the worst case, the basic ecosystem functions have been destroyed and the changes are irreversible.	This status is not acceptable from the management perspective. Management interventions are necessary to restore flow pattern and river habitats (if still possible/feasible) to 'move' a river to a higher management category.

3. Results and discussion

To evaluate the influence of the first three factors on environmental flow volume, the SSARR was used as the hydrological model, HEC-ResSim was used as the hydraulic structures operational model, and

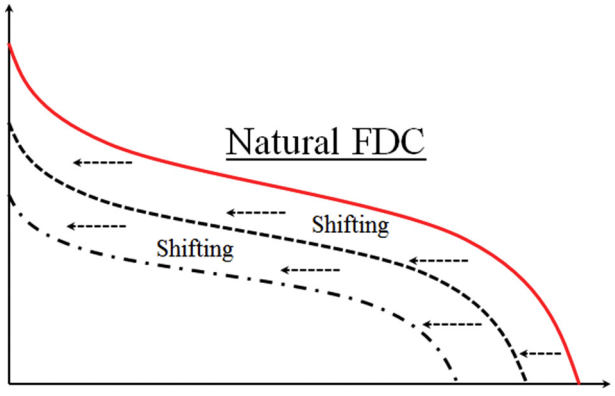

Fig. 5. Estimation technique of environmental management classes (EMC) for environmental flow.

Table 6
EMC calculation example.

%	REF	A	B	C	D	E	F
0.01	4627	4627	2801	1620	1237	604	360
0.1	4627	2801	1620	1237	604	360	261
1	2801	1620	1237	604	360	261	217
5	1620	1237	604	360	261	217	186
10	1237	604	360	261	217	186	160
20	604	360	261	217	186	160	134
30	360	261	217	186	160	134	101
40	261	217	186	160	134	101	69.8
50	217	186	160	134	101	69.8	51.8
60	186	160	134	101	69.8	51.8	40.2
70	160	134	101	69.8	51.8	40.2	40.1
80	134	101	69.8	51.8	40.2	40.1	40
90	101	69.8	51.8	40.2	40.1	40	40
95	69.8	51.8	40.2	40.1	40	40	39.9
99	51.8	40.2	40.1	40	40	39.9	39.8
99.9	40.2	40.1	40	40	39.9	39.8	39.7
99.99	40.1	40	40	39.9	39.8	39.7	39.6

GEFC as the method to evaluate environmental flows. RCP climate change scenarios, provided by the CCIC, a branch of Korea Meteorological Administration, were applied to analyze the future runoff characteristics of the Geum River Basin under different hydraulic structure operation modes.

3.1. Simulation of the operation of dams and weirs

Based on the flow for each sub-basin calculated, this study calculated the inflow volume to Yongdam Dam and Daecheong Dam; for the inflow volume to Gongju Water Level Station, Sejong, Gongju and Bakje Weirs were based on the medium-region area division and applied to the HEC-ResSim model. The operational methods of each hydraulic structure in each case were based on the operational rates of multi-functional weirs proposed by Ahn et al. (2014). The point in which discharge was stopped and reservoir volume was increased, i.e., the management level, was at a low water level for dams, with the multi-functional weirs at river drought levels prior to weir construction; the managed flow at the Gyuam Water Level Station increased by the amount increased under integrated operations of the structures. The operational effects for each case were assessed based on reliability, and a 100% safe yield was applied over 25 years.

Reservoirs and weirs influence the use and control of water because they supply water to other regions for human use and hydraulic structures such as dams control the inflow and discharge volumes. Due to this, a flow-duration curve was used to analyze the flow variation characteristics at the Gyuam Water Level Station. Fig. 6 shows the flow-duration curves for the four operation cases considered in this study. The curves were based on the flow volume calculated at Gyuam Water Level Station. Compared to Case 1, which represents natural flow state, Cases 2–4 show improvements in flow-duration as flow is controlled by hydraulic structures. C_{fd} is a flow-duration coefficient proposed by Lee et al. (1993) and is computed as follows:

$$C_{fd} = \frac{Q_{10}}{Q_{355}} = \frac{Q_{0.01\%}}{Q_{95\%}} \tag{5}$$

Here, Q_{10}, Q_{355}, $Q_{0.01\%}$, and $\frac{Q_{0.01\%}}{Q_{95\%}}$ show flow-duration standard flows; the subscript shows the number of maintained days during the year.

The flow duration coefficient indicates the extent of flow-duration changes and is also known as the coefficient of river regime. A smaller flow-duration coefficient C_{fd} leads to higher variation in flow, while a bigger coefficient leads to smaller variation in flow, resulting in stability. Increasing flow-duration coefficient may indicate ongoing changes to the river water, resulting in difficulties with continuous development and management of water resources. The flow-duration coefficient used in this study was 286.6 for Case 1, 263.4 for Case 2, 236.3 for Case 3, and 204.2 for Case 4. Compared to that in the uncontrolled Case 1, flow-duration was more stable in the higher cases. These results are in line with the results of Hahm and Kim (2010), which shows that the construction of Daecheong Dam and Yongdam Dam resulted in decreased flow volume during floods and increased flow during drought. Our finding indicates that flow-duration stability can be improved by coupled operations of the multi-functional weirs and existing dams.

Flow-duration analysis at Gyuam Water Level Station showed that at Q95%, (minimum flow), the flow volume in Cases 1, 2, 3, and 4 was 19.1 m^3/s, 26.6 m^3/s, 28.9 m^3/s, and 31.6 m^3/s, respectively. Compared to operating the dam as a standalone entity under planned water supply, joint operations of the dams could result to a flow volume increase of by 2.3 m^3/s, and 5 m^3/s when operations of the dams and the weirs are coupled, resulting in effective water management during droughts.

Fig. 7 shows the EMC calculated at Gyuam Water Level Station by applying the cases to GEFC. In this figure, Case 1 is the reference curve based on natural flow volume. The flow-duration curves of EMC A–F are shifted, showing flow volume changes (with reference to natural flow volume) under each ecological condition. In Cases 2–4, the period of high flow volume was given an EMC of A and at the high flow volume, an EMC was C. The standalone operations of the dam (Case 2) did not lead to improvements in environmental flow volumes during low

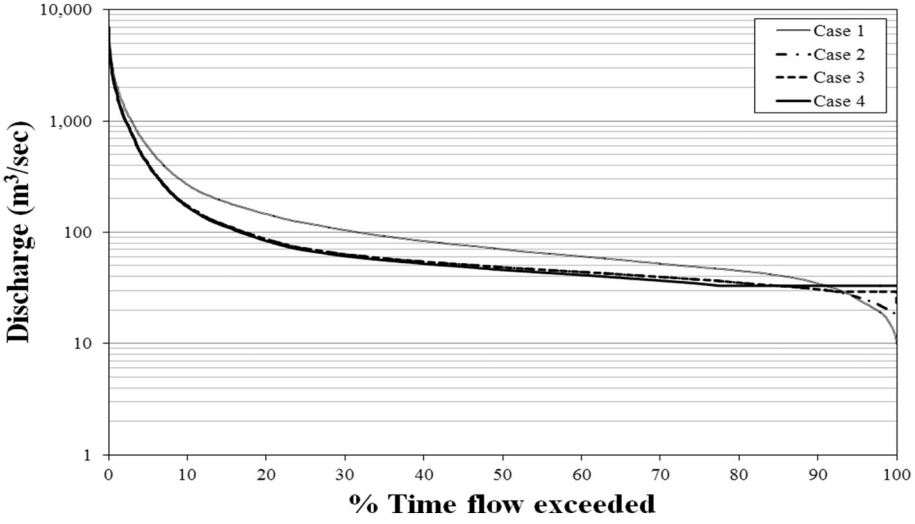

Fig. 6. Flow duration curve by case at the Gyuam Water Level Station.

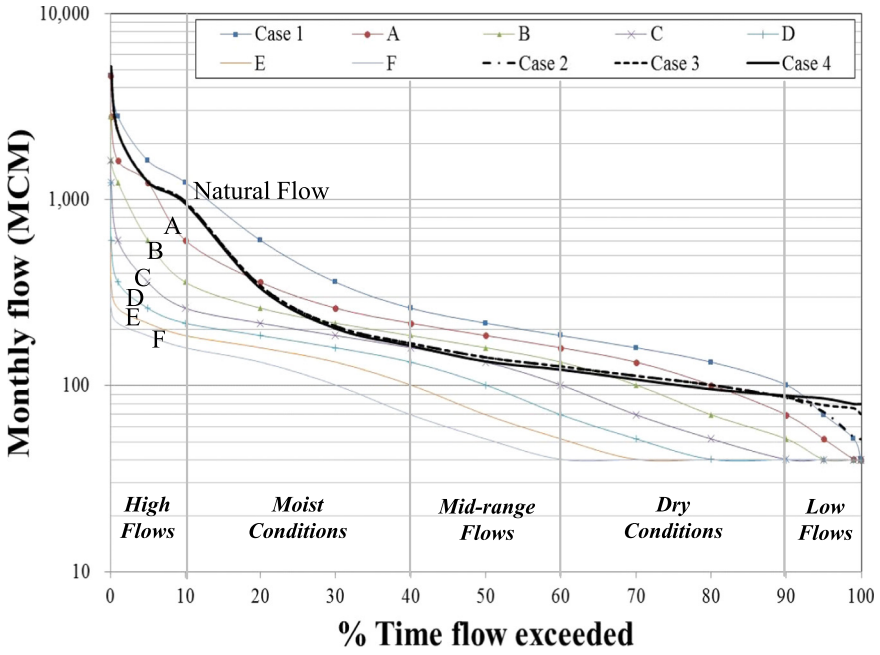

Fig. 7. Environmental flow in the Geum River Basin estimated using GEFC. Case 1: natural state, Case 2: operating dams as standalone, Case 3: integrating the operations of dams, Case 4: integrating the operations of dams and weirs. Please see Table 5 for explanations of EMC A to F.

flows at Q95%. In contrast, at Q95%, the integrated operations of the hydraulic structures (Cases 3 and 4) led to higher maintained flow. This indicates that river maintenance flow volume should be maintained during droughts for environmental improvements. Water quality is usually closely tied to flow volume; it worsens during droughts or low flows. Increasing the flow volume through operational methods is expected to improve water quality. For instance, Choi (2008) reports that higher maintained flows can lead to a dramatic increase in water quality and habitat suitability for fish species. Moreover, with high maintenance flow volume, water can be utilized for managing the environment, while at the same time the river can be designed for activities that can lead to improvements in the social landscape, such as water play, tourism, and river cultural events. Under South Korea's River Act, amended in April 2007, the water for environment improvement is legislated as water for a purpose, in which river maintenance flows are defined. Generally, the Act requires a larger flow volume compared to what can be secured through natural river processes. Therefore, the increased water flow from the integrated operations of the hydraulic structures is needed to satisfy the said flow volume requirement.

The ratio of mean annual runoff by EMC to the mean annual runoff under natural flow conditions is shown in Table 7. As can be seen, higher ratios were obtained in Case 4 than in Case 2 or 3. Jones (2002) reported that a drop of the mean annual runoff to below two-thirds of the natural level of a given river may lead to a decreased likelihood of the river maintaining a healthy state. Moreover, Tennant (1976) reported that the minimum mean annual runoff required to maintain the lowest minimum water quality and flow requirement for a healthy aquatic ecosystem is 10% of the natural flow volume. Therefore, given the need to secure water to prepare for future uncertainty such as climate change, the increased mean annual runoff ratio from the integrated operation of hydraulic structures is deemed to have significant positive effects in preserving water resources.

Table 7
Mean annual runoff by EMC to the mean annual runoff under natural flow conditions (Ahn et al., 2014).

Case	A	B	C	D	E	F
Case 1	70.9	49.2	35.8	27.8	22.6	18.6
Case 2	67.9	47	35.2	29.1	25.4	22.7
Case 3	68.5	48.2	37	31.5	28.4	26.3
Case 4	68.5	48.3	37.4	32.4	29.8	28.1

3.2. Climate change impacts on the water resource system

To calculate the natural runoff volume, the climate change scenarios of RCP 4.5 (Scenario 2–1) and RCP 8.5 (Scenario 2–2) specific to South Korea with 1 km spatial resolution from January 1, 2006 to December 31, 2100 were applied to the SSARR model, and the runoff volume at key points for the water use of the Geum River System was calculated.

Analyzing Scenario 2–1 based on the average runoff volume between 2006 and 2014 and 2015–2049, there was a 13.3% increase in inflow at 404705 ("404,705" is a code for inflow location at Yongdam dam, as shown in Fig. 3), 18.6% at 404714, 23.4% at 404721, and 24.6% at 404723; and comparing 2006–2014 with 2050–2100, there were increases of 19.3% at 404705, 25.2% at 404714, 33.3% at 404721, and 34.5% at 404723. Analyzing Scenario 2–2 based on comparing the average runoff volume between 2006 and 2014 and 2015–2049, there was a 19.2% increase in inflow at 404705, 16.4% at 404714, 17.5% at 404721, and 24.6% at 404723; and comparing 2006–2014 with 2050–2100, there were increases of 26.3% at 404705, 15.8% at 404714, 16.5% at 404721, and 34.5% at 404723.

One notable observation was that the increases in inflow from October to April were larger than the increases from July to September, which is the flooding season of Korea. Moreover, as shown in Fig. 8, the monthly runoff volume in the flood season from June to September was significantly smaller for RCP 8.5 than for RCP 4.5. This indicates a change in the overall water cycle and highlights the fact that water resources have different seasonal characteristics. In Korea, there are plans to secure stable freshwater supply from rainfall-runoff volumes concentrated during June to October. However, future management of water resources must be restructured towards responding to climate change in order to mitigate the effects of changing rainfall patterns and concomitant water shortage. Therefore, for more effective water resource management, continuous monitoring and analysis of the change in rainfall-runoff volumes due to climate change is required. Moreover, should these trends become reality in the future, it would be important

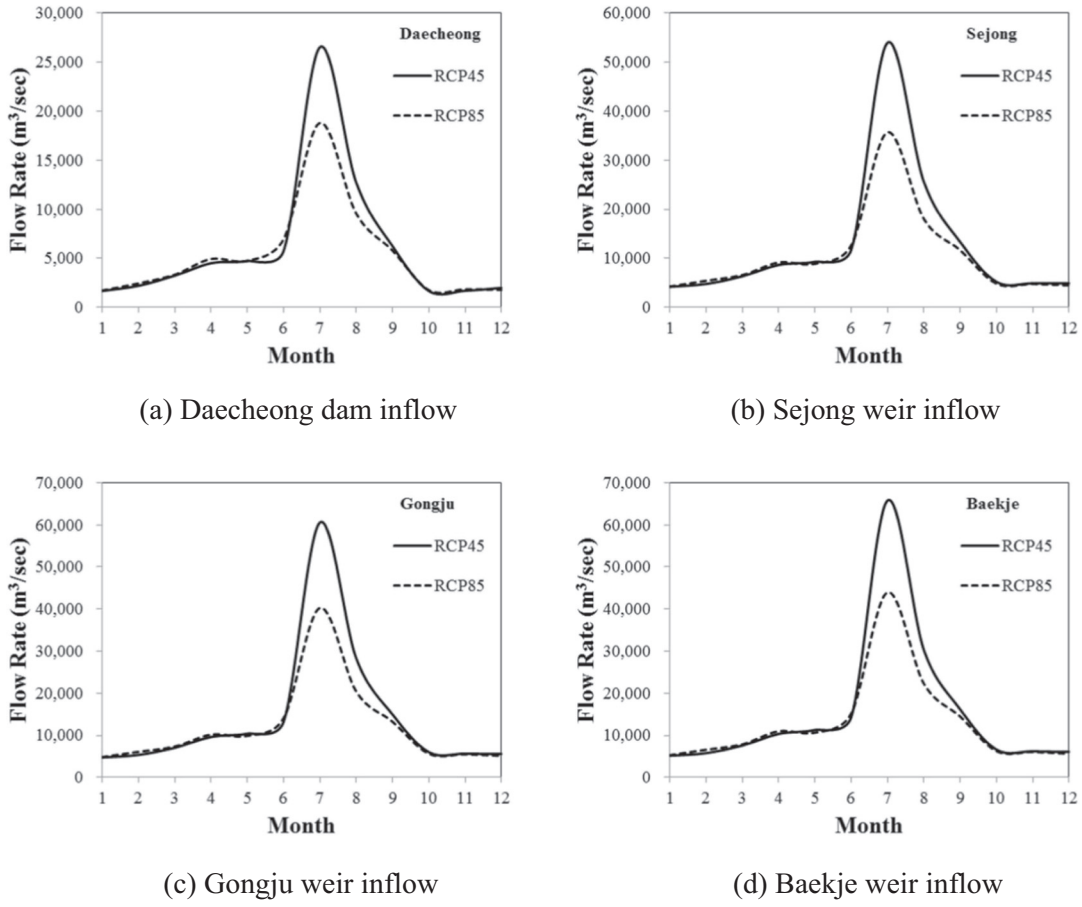

Fig. 8. Monthly runoff volume under Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios calculated by the SSARR model (please see Section 2.3.2 for a more detailed explanation of the scenarios).

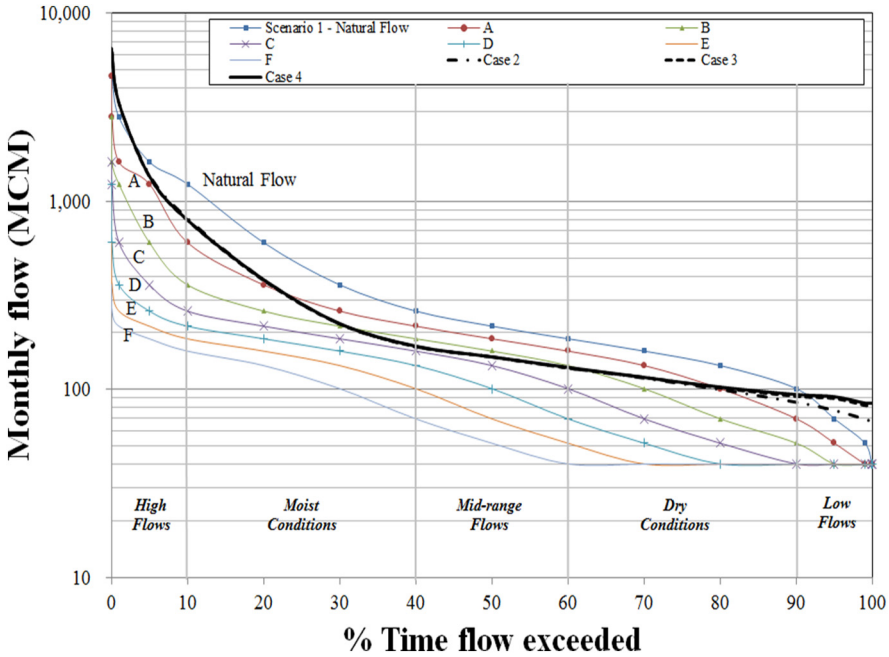

Fig. 9. Comprehensive environmental flow estimated by case under Scenario 2–1 compared to the environmental management classes estimated under Scenario 1 at the Gyuam point. Case 1: natural state, Case 2: operating dams as standalone, Case 3: integrating the operations of dams, Case 4: integrating the operations of dams and weirs. Please see Table 5 for explanations of EMC A to F.

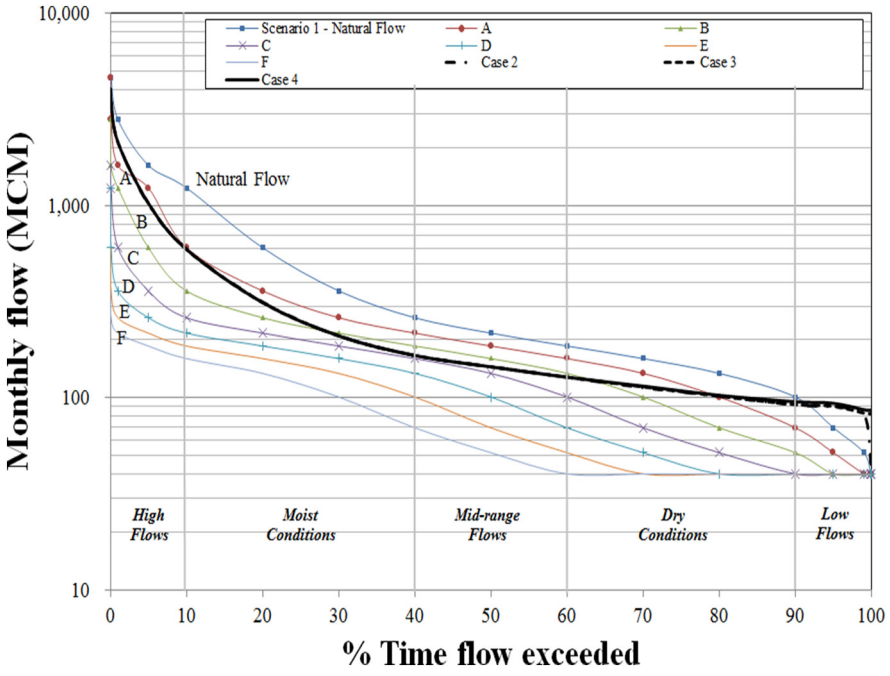

Fig. 10. Comprehensive environmental flow estimated by case under Scenario 2–2 compared to the environmental management classes estimated by Scenario 1 at the Gyuam point. Case 1: natural state, Case 2: operating dams as standalone, Case 3: integrating the operations of dams, Case 4: integrating the operations of dams and weirs. Please see Table 5 for explanations of EMC A to F.

to adopt a system that can efficiently distribute water resources as needed, and to review the operations of reservoir groups.

Figs. 9 and 10 show the results of environmental flow volume estimation by case under Scenario 2–1 and Scenario 2–2 with reference to the EMCs determined under Scenario 1 in Fig. 7. Fig. 8 shows the differences in seasonal runoff volume between Scenarios 2–1 and 2–2. As can be seen from Fig. 9, Scenario 2–1 FDC is located between the curves of the natural runoff volume and EMC A in "High Flows," while Scenario 2–2 FDC is located between EMC A and EMC B curves. In "Moist Conditions," Scenario 2–1 is located between the curves of the natural runoff and EMC A, while Scenario 2–2 is located between EMC A and B curves. There have clearly been slight ecological modifications in Scenario 2–2 compared to Scenario 2–1 in "High Flows" and "Moist Conditions." In contrast, due to the operations of hydraulic structures, no significant changes to the environmental flows under the climate change scenarios were observed at "Mid-range Flows," "Dry Conditions," and "Lows."

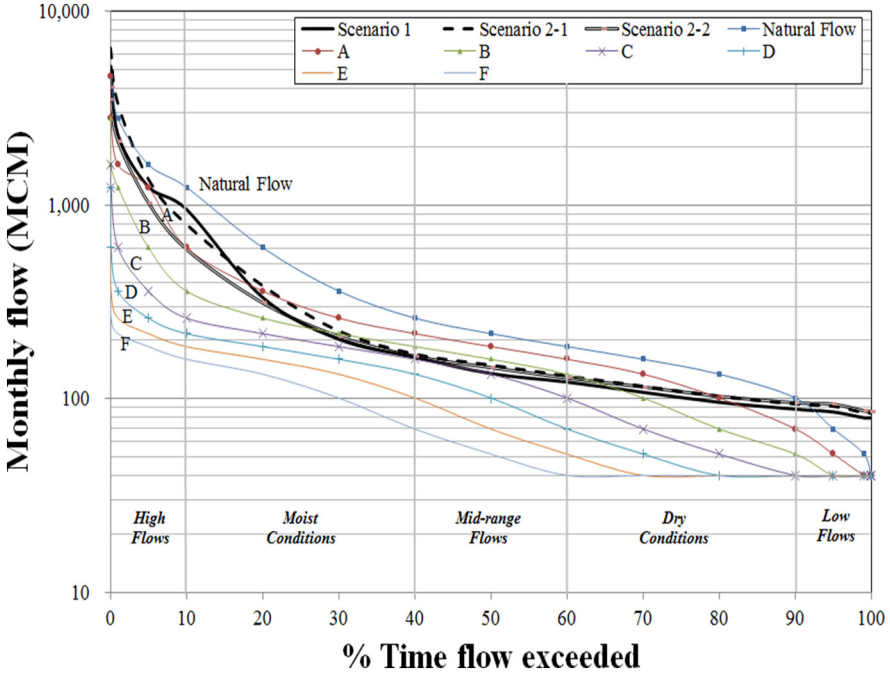

Fig. 11. Comprehensive environmental flow estimated under Scenario 2–1 and 2–2 scenario for Case 4 compared to environmental management classes estimated under Scenario 1 at the Gyuam point. Case 1: natural state, Case 2: operating dams as standalone, Case 3: integrating the operations of dams, Case 4: integrating the operations of dams and weirs. Please see Table 5 for explanations of EMC A to F.

While the natural runoff volume did not differ greatly from the present in Scenario 2–1 (carbon reduction achieved), the flow volume was reduced during flooding season in Scenario 2–2 (carbon reduction not achieved). As Korea has been specified as a country of insufficient water resources, and thus has a large coefficient of river regime (1:299), it has typically saved the rainfall concentrated over the summer (July–September) in dams and reservoirs and discharged downstream as needed to meet water demands. However, reductions in runoff volume during floods would require water resource management plans to respond to climate change. In Korea, multi-purpose dams are constructed to collect freshwater to secure water resources and address unstable flow problems. The water collected in the period between July to September are used until the following June. In the case of the Geum River system, the three multi-functional weirs of the Four Major Rivers Restoration Project were constructed to respond to droughts, adding onto the existing Yongdam Dam and Daecheong Dams. Therefore, the runoff decrease during flooding season under Scenario 2–2 could lead to a demand for policies that seek to further secure water resources.

Fig. 11 gives a visual comparison of Scenarios 2–1, and 2–2 with reference to the EMC determined under Scenario 1 in Fig. 7. It is clear that Scenario 2–1 does not have large changes in the EMC compared to Scenario 1. On the other hand, with reference to Scenario 2–1 curve, Scenario 2–2 curve is located to the left at lower EMC under "High Flows" and "Moist Conditions." Determining the EMC under the operations of the dam and the multi-functional weirs, EMC C is shown in mid-range flows for Scenarios 1, 2–1, and 2–2. EMC C is associated with multiple disturbances linked to socio-economic development, including the construction of dams and diversions, habitat changes, and water quality degradation. These disturbances can lead to shifts in the habitats and dynamics of biota. Although basic ecosystem functions may still persist, some sensitive species may be lost and alien species may be introduced. It appears that it would maintain above EMC D, where there are significant and clearly visible disturbances associated with basin and water resources development. Under "Dry Conditions," the EMC remained stable at B, meaning that water supply plans would be permitted as the maintenance flow volume of the river would be stable from the operations of the dam and multi-functional weirs. It appears that more runoff volume can be kept in the river compared to natural runoff volume for "Low Flows." In this case, it would be possible to operate the dams and multi-functional weirs to the extent that they do not disturb the river ecosystem. Moreover, discharging the water stored in the dam and multi-functional weirs during droughts can help respond to water shortages.

Table 8 organizes the EMC at Gyuam Water Level Station using the modelled monthly time-series flows under the natural flow volume scenario and shows the ratio of natural MAR to MAR per EMC. The MAR ratio is generally higher for all EMCs in Scenario 2–1 than in 2–2. Moreover, comparing Cases 1–4 shows that the integrated operation of dams and weirs (Case 4) leads to a larger MAR ratio. As the annual rainfall is expected to be concentrated and irregular droughts are more likely to take place with climate change, the future water resources strategy should prioritize implementing a carbon reduction policy to mitigate climate change. Additionally, the strategy should effectively manage water resources by jointly operating the existing dams and multi-functional weirs to ensure continued access to water resources.

Table 8
Estimation of long-term EF for different EMCs for Scenario 2–1 and 2–2.

Scenario	Case	A	B	C	D	E	F
Scenario 2–1	Case 1	67.7	46.2	33	24.6	18.6	13.8
	Case 2	68.5	50.5	40.5	35.3	32.2	30
	Case 3	69.7	52.7	43.4	38.8	36.2	34.5
	Case 4	69.7	52.8	43.7	39.1	36.7	35.1
Scenario 2–2	Case 1	61.3	40.6	29	21.6	16.4	12.2
	Case 2	62.1	45.8	38.6	34.8	32.6	31.1
	Case 3	62.2	45.9	38.7	34.9	32.7	31.3
	Case 4	62.4	46.3	39.3	35.7	33.6	32.3

4. Conclusion

While previous works studied climate change, runoff, reservoir operations, and environmental flow volume separately, this study has presented a comprehensive method to evaluate the river environment by considering all the above factors. The analysis has led to the following conclusions:

1. Compared to separate operations of hydraulic structures, jointly operating the dam and multi-functional weir led to higher efficiency in water resource management and water use during droughts. The water resources secured by joint operations of dam and multi-functional weir maintained a level of EMC as it is shifted to the left during droughts, contributing to positive environmental conditions. Similar results were found in the MAR ratio for EMC on natural MAR.

2. Scenario 2–1 curve is located between natural runoff volume and EMC A curves in "High Flows," while Scenario 2–2 is located between EMC A and B curves. Thus, the reduced flow volume during flooding season lowered the EMC by one class, resulting in a slight ecological modification. Both Scenario 2–1 and 2–2 fall on EMC C in "Mid-range Flows," resulting in disturbances to habitats and dynamics of biota. This class is also associated with normal ecosystem functions but loss of some sensitive species and occurrence of some alien species. Therefore, there is a need for socio-economic development, including the construction of dams and diversions, habitat modification and reduced water quality, from the perspective of water resources management. Under "Dry Conditions," EMC was B, and under "Low Flows," it appeared that a higher level of runoff volume could be maintained compared to natural runoff volume. Discharging the water volume kept in the dam by integrated operation of dam and multi-functional weir during busy farming season, when adequate water supply is usually lacking, can help respond to shortages in water for agricultural use. If carbon reduction is not realized, water resources and environmental management will be changed by climate change.

3. The results of this study are expected to provide decision-makers with data that are valuable for the development of effective water resources management strategies that take into consideration environmental flow volume in the Geum River Basin. However, the analysis was based on the EMC developed by Smakhtin and Eriyagama (2008), and thus may not accurately reflect the Korean situation. Therefore, it may be necessary to review the shifting methods and standards to fit the reality of Korea.

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References

Ahn, J.M., Lee, S.J., Kang, T., 2014. Evaluation of dams and weirs operating for water resource management of the Geum River. J. Sci. Total Environ. 478, 103–115.
Ahn, J.M., Lee, S.J., Kang, T., 2016. Development of water quality forecasting system with ensemble stream prediction method in the Geum River Basin, Korea. Desalin. Water Treat. 57 (2):670–683. https://doi.org/10.1080/19443994.2014.996010.
Ahn, J.M., Jung, K.Y., Shin, D.S., 2017. Effects of coordinated operation of weirs and reservoirs on the water quality of the Geum River. Water 9:423. https://doi.org/10.3390/w9060423.
Ahn, J.M., Yang, D.S., Jung, K.Y., Shin, D.S., 2018. Assessing the coordinated operation of reservoirs and weirs for sustainable water management in the Geum River Basin under climate change. Water 10:30. https://doi.org/10.3390/w10010030.
Bunn, S.E., Arthington, A.H., 2002. Basic principles and ecological consequence of altered flow regimes for aquatic biodiversity. Environ. Manag. 30, 492–507.
Choi, H.S., 2008. Effect on water quality and fish habitat improvement of Wonju Cheon by instream flow increasing. J. Korean Soc. Water Environ. 27 (3), 273–285 (in Korean).
Climate Change Information Center, d. www.climate.go.kr, Accessed date: 14 April 2017.

Hahm, C.H., Kim, G.H., 2010. A study of ecological flow assessment for environmental development in natural river. J. Korean Soc. Geo Spatial Inf. Syst. 18 (1), 47–53 (in Korean).
HEC, 1994. HEC-DSS User's Guide and Utility Manuals. Hydrologic Engineering Center, Davis, CA.
Hughes, D.A., 2001. Providing hydrological information and data analysis tools for determination of ecological instream flow requirements for South African rivers. J. Hydrol. 241, 140–151.
Jones, G., 2002. Setting environmental flows to sustain a healthy working river. Water Shed. Cooperative Research Center for Freshwater Ecology, Canberra February. http://freshwater.canberra.edu.au.
Kashaigili Japhet, J., Matthew, Mccartney, Mahoo Henry, F., 2007. Estimation of environmental flows in the Great Ruaha River Catchment, Tanzania. Phys. Chem. Earth 32, 1007–1014.
Kim, J.C., Choi, Y.J., 2010. The applicability assessment of environmental flows method by hydrological approach. J. Korean Soc. Water Environ. 26 (2), 208–214 (in Korean).
Klipsch, J.D., Hurst, M.B., 2007. HEC-ResSim, Reservoir System Simulation User's Manual. U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, Davis, CA , Version 3.0.
Korea Water Resources Corporation, 2017. Handbook for Dam Operation Practices in Korea (in Korean).
Lee, A.Y., Kim, S.D., 2011. An analysis of the effect of climate change on Nakdong River environmental flow. J. Korean Soc. Water Environ. 27 (3), 273–285 (in Korean).
Lee, J.W., Kim, H.S., Woo, H.S., 1993. An analysis of the effect of damming on flow duration characteristics of five major rivers in Korea. J. Korean Soc. Civil Eng. 13 (3), 79–91 (in Korean).
Lin, N.M., Rutten, M., 2016. Optimal operation of a network of multi-purpose reservoir: a review. Procedia Eng. 154, 1376–1384.
Miguel, A.A.G., Julio, S.C., Cristina, S., 2018. Environmental flow management: an analysis applied to the Ebro River basin. J. Clean. Prod. 182, 838–851.
Ministry of Land, Infrastructure, and Transport, 2000. Infrastructure, and transport. Development of a Method for Determining the Instream Flow and its Application (in Korean).
Ministry of Land, Infrastructure, and Transport, 2006. Infrastructure, and transport. Water Vision 2020 (in Korean).
Ministry of Land, Infrastructure, and Transport, 2007. Infrastructure, and transport. Report of the Study to Secure Instream Flow to Estimate Natural & Social Environment (in Korean).
Ministry of Land, Infrastructure, and Transport, 2016. Water Vision 2020, 3rd Revision Plan (in Korean).
Salik, K.M., Hashmi, M.Z.R., Ishfaqa, S., Zahdi, W.U.Z., 2016. Environmental flow requirements and impacts of climate change-induced river flow changes on ecology of the Indus Delta, Pakistan. Reg. Stud. Mar. Sci. 7, 185–195.
Smakhtin, V.U., Anputhas, M., 2006. An Assessment of Environmental Flows and Implications for Indian River Basins, IWMI Research Report 107. International Water Management Institute, Colombo, Sri Lanka.
Smakhtin, V.U., Eriyagama, N., 2008. Developing a software package for global desktop assessment of environmental flows. Environ. Model. Softw. https://doi.org/10.1016/j.evnsoft.2008.04.002/.
Sood, A., Smakhtin, V., Eriyagama, N., Villholth, K.G., Liyanage, N., Wada, Y., Ebrahim, G., Dickens, C., 2017. Global Environmental Flow Information for the Sustainable Development Goals. IWMI Research Report 168, International Water Management Institute, Colombo, Sri Lanka.
Stamou, A., Polydera, A., Papadonikolaki, G., Martinez-Capel, F., Munoz-Mas, R., Papadaki, Ch., Zogaris, S., Bui, M.-D., Rutschmann, P., Dimitriou, E., 2018. Determination of environmental flows in rivers using an integrated hydrological-hydrodynamic-habitat modelling approach. J. Environ. Manag. 2018 (209), 273–285.
Tennant, R.E., 1976. Instream flow regimes for fish, wildlife, recreation and related environmental resources. Fisheries 1, 6–10.
The Nature Conservancy, 2006. Environmental flows/water for people-water for nature. http://www.nature.org/freshwater.
Welsh, W.D., Vaze, J., Dutta, D., Rassam, D., Rahman, J.M., Jolly, E.D., Wallbrink, P., Podger, G.M., Bethune, M., Hardy, M.J., Teng, J., Lerat, J., 2013. Environ. Model. Softw. 39, 81–102.